High Energy Dilepton Experiments

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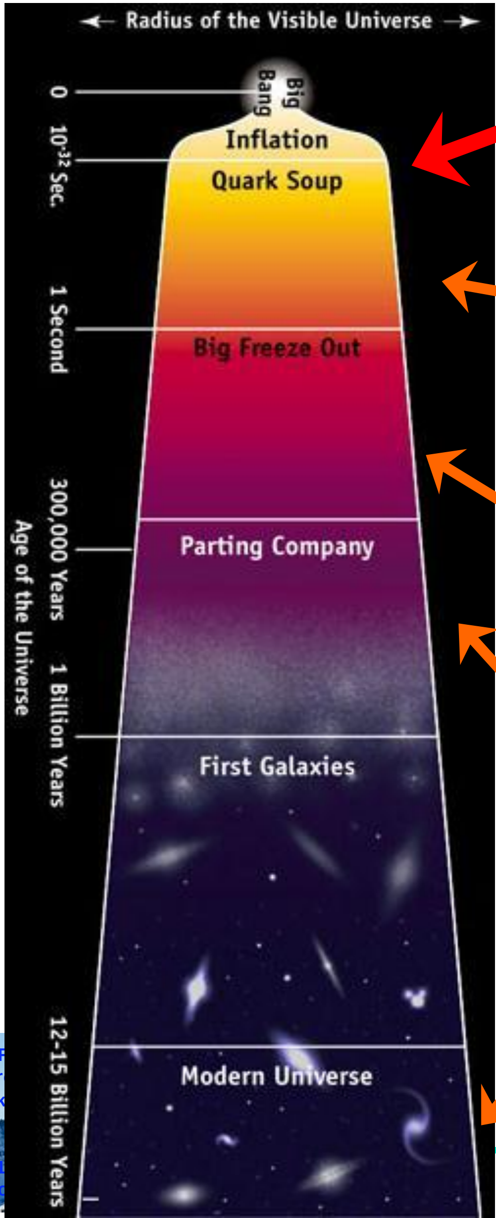
Evolution of the Universe

from the Big Bang to today's world



Too hot for quarks to bind!!!
Standard Model (N/P) Physics

Quark-Gluon Plasma

Too hot for nuclei to bind
Nuclear/Particle (N/P) Physics

Hadron Gas

Nucleosynthesis builds nuclei up to He
Nuclear Force...Nuclear Physics

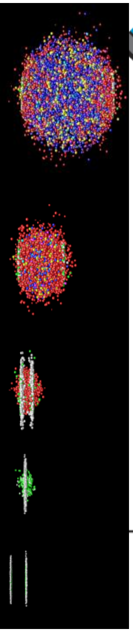
E/M Plasma

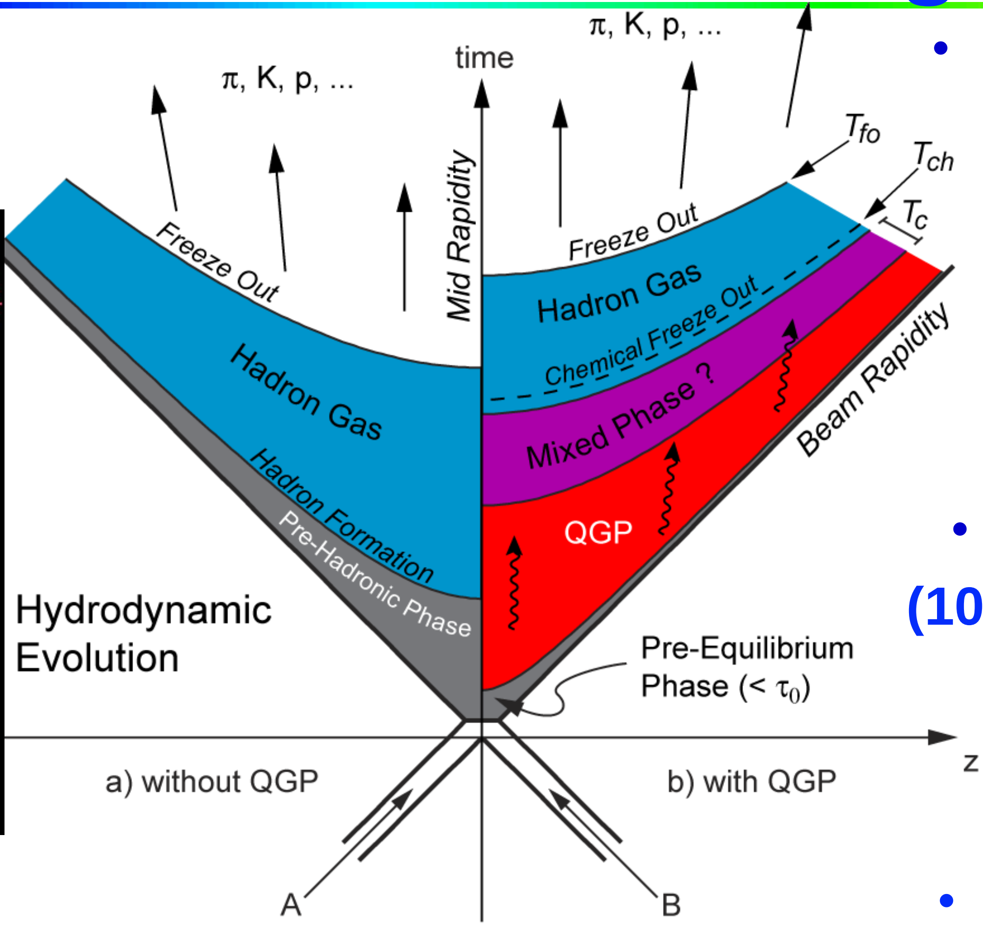
Universe too hot for electrons to bind
E-M...Atomic (Plasma) Physics

Today's Cold Universe
Gravity...Newtonian/General Relativity

Solid Liquid Gas

The "Little Bang" in the lab

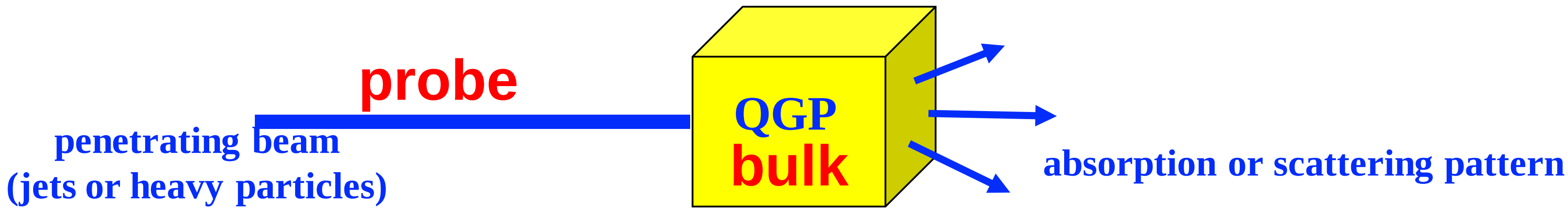




- **High energy nucleus-nucleus collisions:**
  - **fixed target (SPS: $\sqrt{s}$=20GeV)**
  - **colliders**
    - **RHIC: $\sqrt{s}$=200GeV**
    - **LHC: $\sqrt{s}$=5.5TeV**
- **QGP formed in a tiny region (10^{-14}m) for very short time (10^{-23}s)**
  - **Existence of a mixed phase?**
  - **Later freeze-out**
- **Collision dynamics: different observables sensitive to different reaction stages**

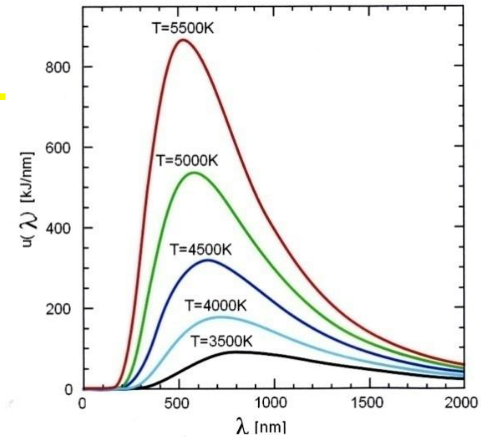
Probing the QGP

- Rutherford experiment $\alpha \rightarrow$ atom discovery of nucleus
- SLAC electron scattering $e \rightarrow$ proton discovery of quarks

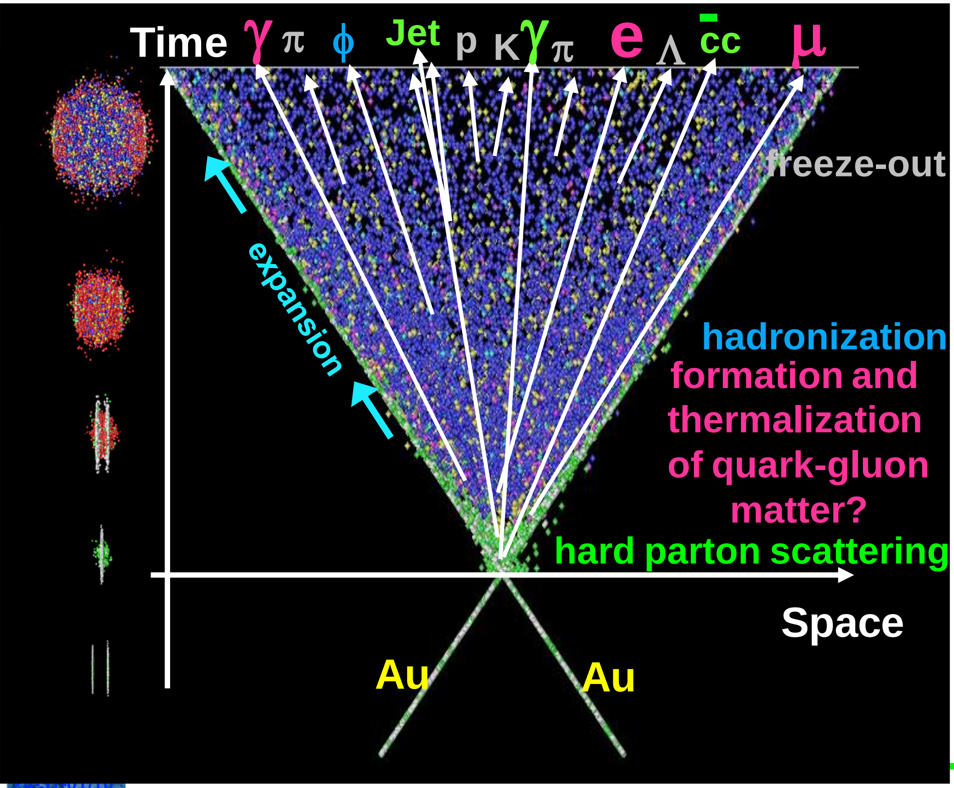


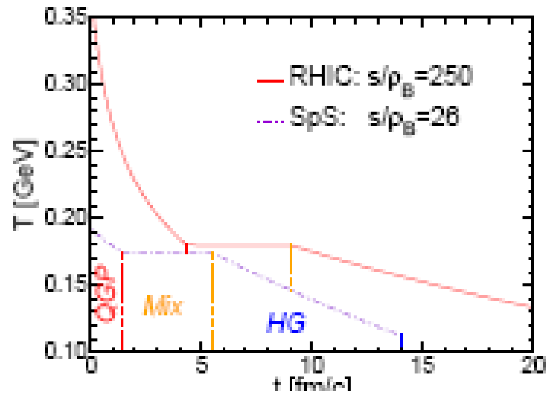
- Penetrating beams created by parton scattering before QGP is formed
  - High transverse momentum particles $\rightarrow$ jets
  - Heavy particles $\rightarrow$ open and hidden charm or bottom
- Probe QGP created in Au+Au collisions
  - Calculable in pQCD
  - Calibrated in control experiments: p+p (QCD vacuum), p(d)+A (cold medium)
- Produced hadrons lose energy by (gluon) radiation in the traversed medium
- QCD Energy loss → medium properties
  - Gluon density
  - Transport coefficient

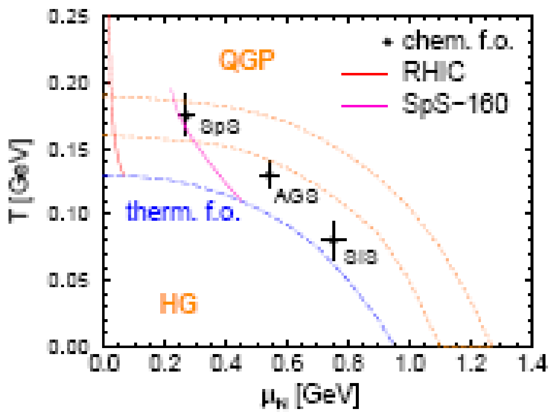
Electromagnetic Radiation



- Thermal black body radiation
  - Real photons γ
  - Virtual photons γ^* which appear as dileptons e^+e^- or $\mu^+\mu^-$
- No strong final state interaction
  - Leave reaction volume undisturbed and reach detector
- Emitted at **all stages** of the space time development
  - Information must be deconvoluted







What we can learn from lepton pair emission

arXiv:0912.0244

Emission rate of dilepton per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

$$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}(1+\frac{2m_l^2}{M^2})$$

$\gamma^* \rightarrow ee$ decay

EM correlator
Medium property

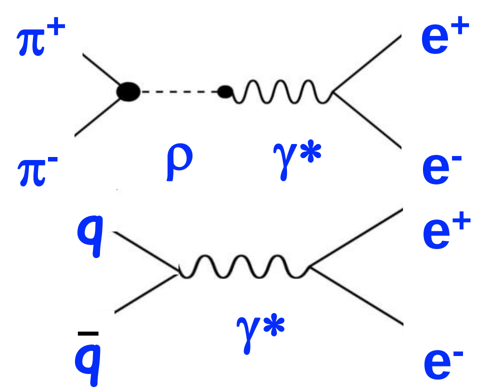
Boltzmann factor
temperature

Hadronic contribution
Vector Meson Dominance

$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{em}}(M) = \begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}D_V(M) \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right)N_c\sum_{q=u,d,s}(e_q)^2 \end{cases}$$

qq annihilation

Medium modification of meson
Chiral restoration



Thermal radiation from partonic phase (QGP)

From emission rate of dilepton, one can decode

- medium effect on the EM correlator
- temperature of the medium

Relation between dilepton and virtual photon

arXiv:0912.0244

Emission rate of dilepton per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

Emission rate of (virtual) photon per volume

$$q_0\frac{dR_{\gamma^*}}{d^3q} = -\frac{\alpha}{2\pi^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T).$$

Relation between them Prob. $\gamma^* \rightarrow l^+l^-$

$$\underbrace{q_0\frac{dR_{ll}}{dM^2d^3q}}_{\text{Dilepton}} = \frac{1}{2}\frac{dR}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2}\underbrace{q_0\frac{dR_{\gamma^*}}{d^3q}}_{\text{virtual photon}}$$

This relation holds for the yield after space-time integral

Virtual photon emission rate can be determined from dilepton emission rate

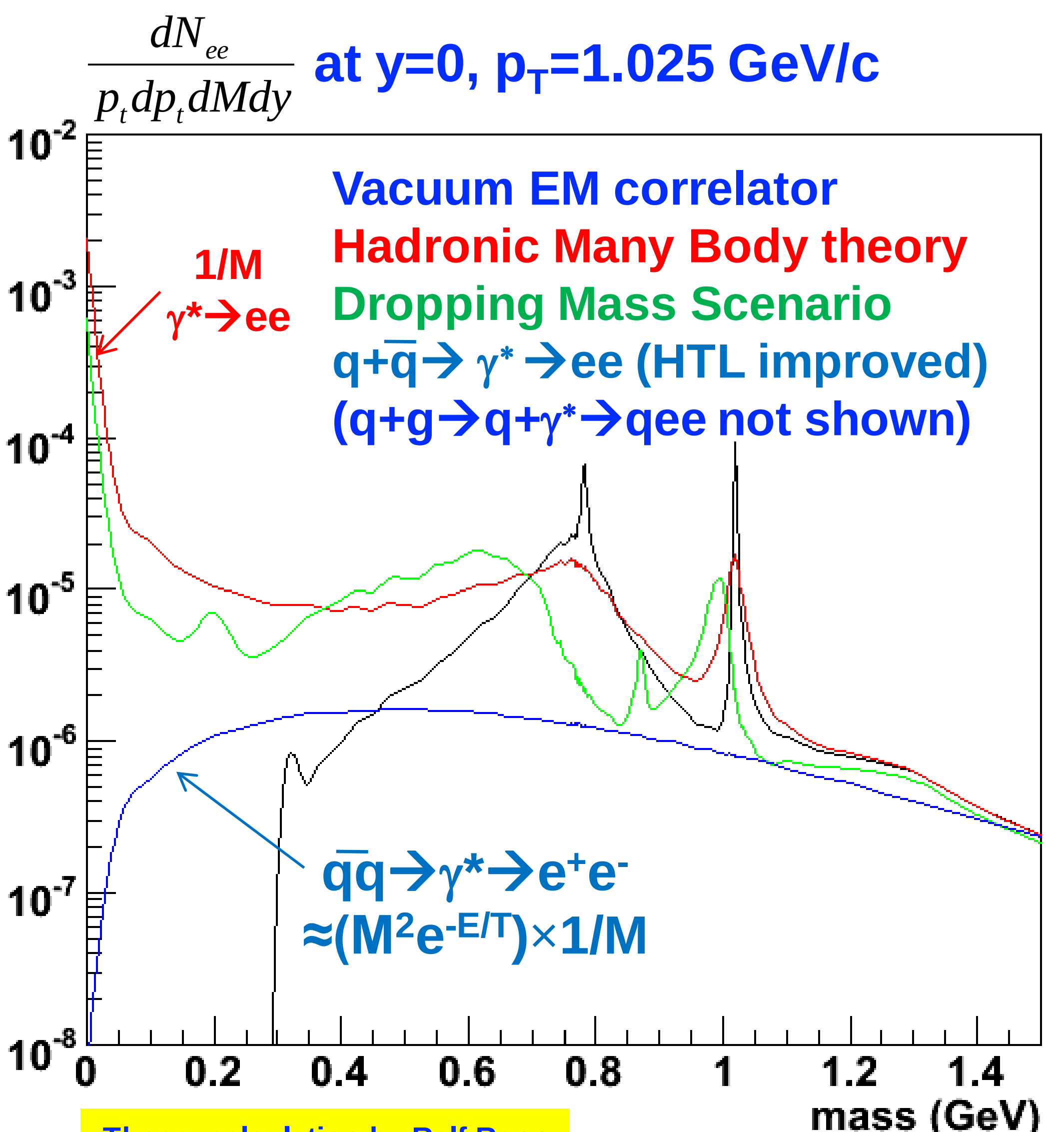
$$\begin{aligned} q_0\frac{dn_{\gamma^*}}{d^3q} &\simeq \frac{3\pi}{\alpha}M^2q_0\frac{dn_{ll}}{d^3qdM^2} \\ &= \frac{3\pi}{2\alpha}Mq_0\frac{dn_{ll}}{d^3qdM}. \end{aligned}$$

$M \times dN_{ee}/dM$ gives virtual photon yield

For $M \rightarrow 0$, $n_\gamma^* \rightarrow n_\gamma$(real) real photon emission rate can also be determined

Theory prediction of dilepton emission

arXiv:0912.0244



Theory calculation by Ralf Rapp

Usually the dilepton emission is measured and compared as $dN/dp_T dM$

The mass spectrum at low p_T is distorted by the virtual photon→ee decay factor 1/M, which causes a steep rise near M=0

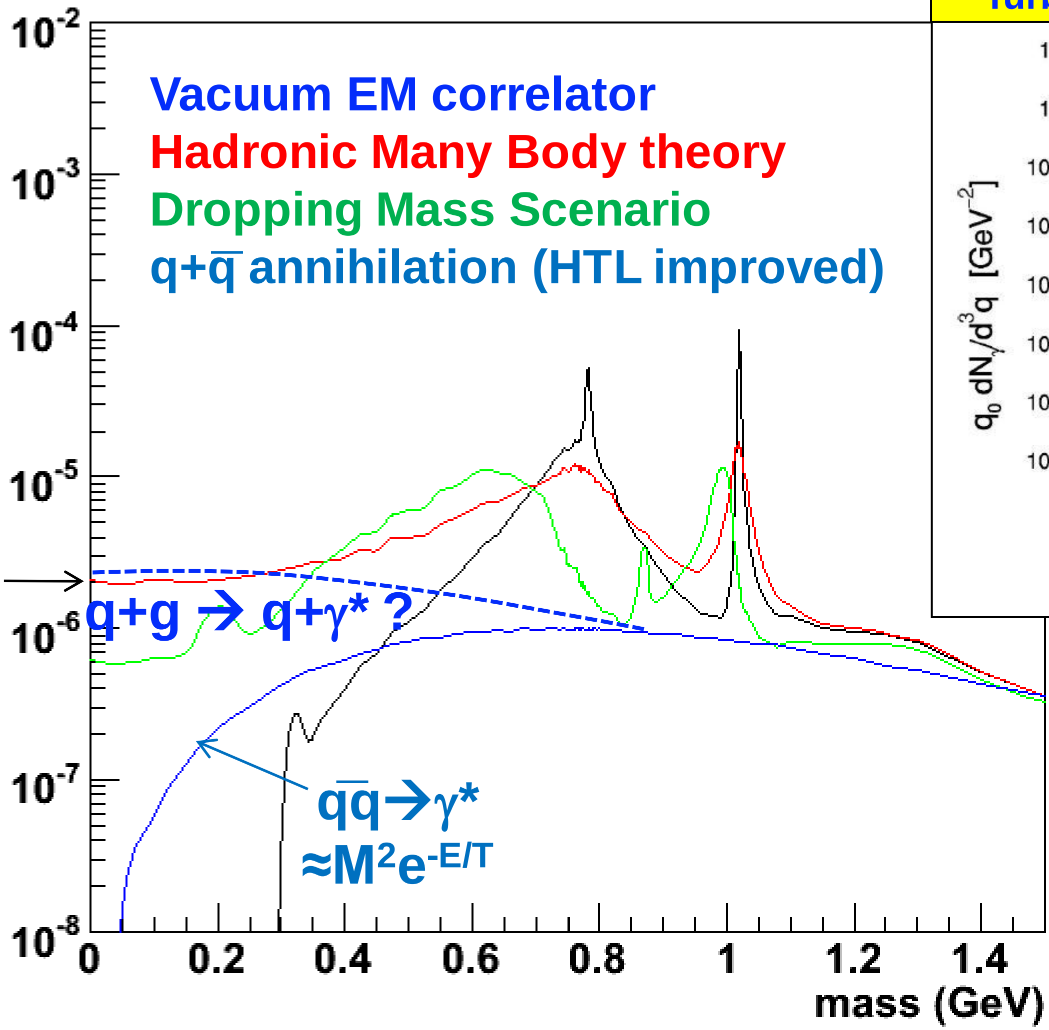
qq annihilation contribution is negligible in the low mass region due to the M^2 factor of the EM correlator

In the caluculation, partonic photon emission process $q+g \rightarrow q+\gamma^* \rightarrow qe^+e^-$ is not included

Virtual photon emission rate

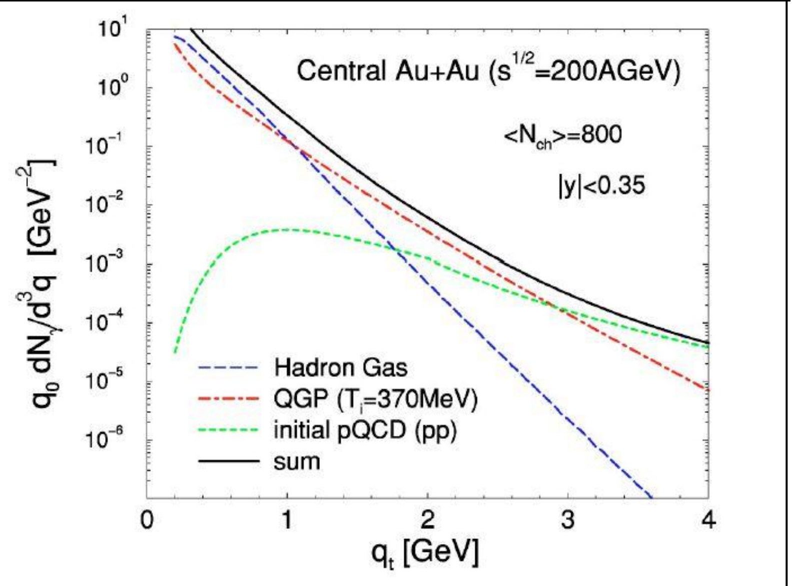
arXiv:0912.0244

$$M \times \frac{dN_{ee}}{p_t dp_t dM dy} \propto \frac{dN_{\gamma^*}}{p_t dp_t dy}$$ at y=0, p_T=1.025 GeV/c



Real photon yield

Turbide, Rapp, Gale PRC69,014903(2004)

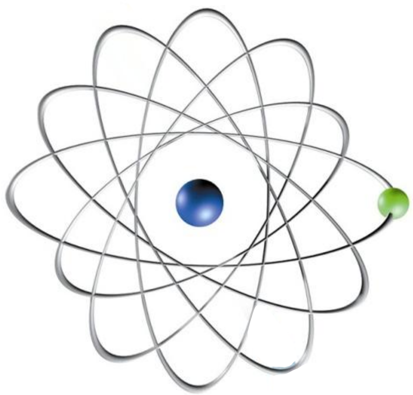


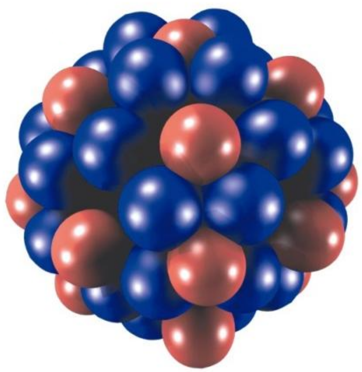
When extrapolated to M=0, the real photon emission rate is determined.

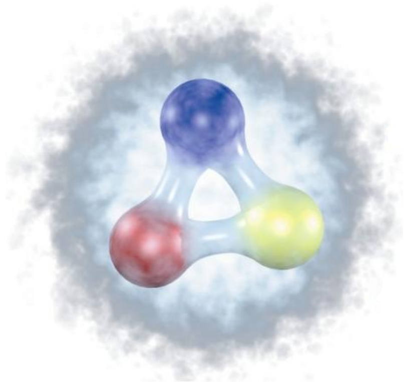
q+g→q+γ* is not shown; it should be similar size as HMBT at this p_T

The mass of composite systems

atom	atomic nucleus	nucleon
10^{-10} m	10^{-14} m	10^{-15} m







atom: $M \approx \Sigma m_i$

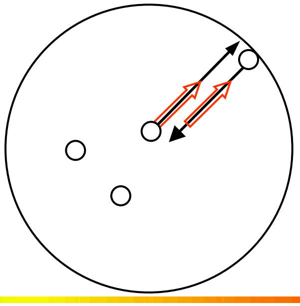
binding energy effect $\approx 10^{-8}$

atomic nucleus: $M \approx \Sigma m_i$

binding energy effect $\approx 10^{-3}$

nucleon: $M \gg m_i$

mass given by energy stored in motion of quarks and by energy in colour gluon fields

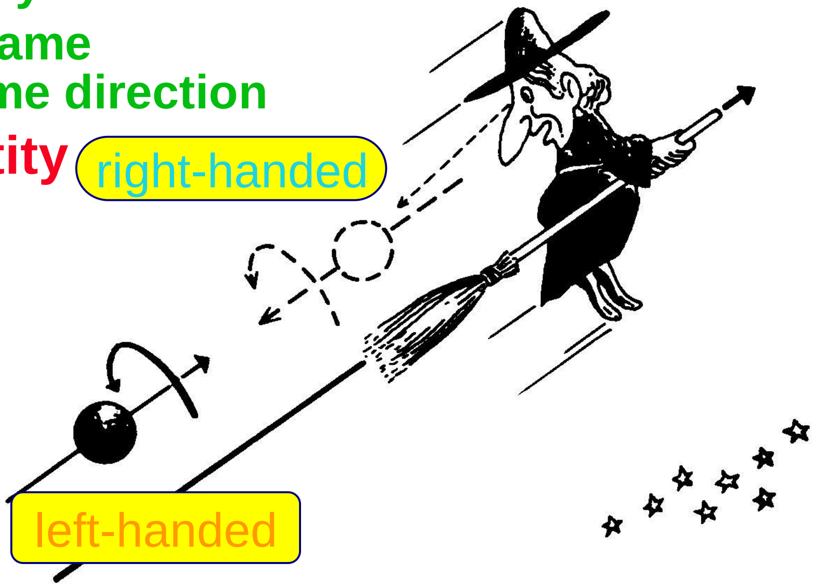


<u>the role of chiral symmetry breaking</u>

- chiral symmetry = fundamental symmetry of QCD for massless quarks
- chiral symmetry broken on hadron level

Chirality

- **Chirality (from the greek word for hand: “χειρ”)**
  when an object differs from its mirror image
- **simplification of chirality: helicity**
  (projection of a particle’s spin on its momentum direction)
- **massive particles P**
  - **left and right handed components must exist**
  - **m>0 → particle moves w/ v<c**
    - **P looks left handed in the laboratory**
    - **P will look right handed in a rest frame moving faster than P but in the same direction**
  - **chirality is NOT a conserved quantity**
- **in a massless word**
  - **chirality is conserved**
    - **careful: m=0 is a sufficient but not a necessary condition**



QCD and chiral symmetry breaking

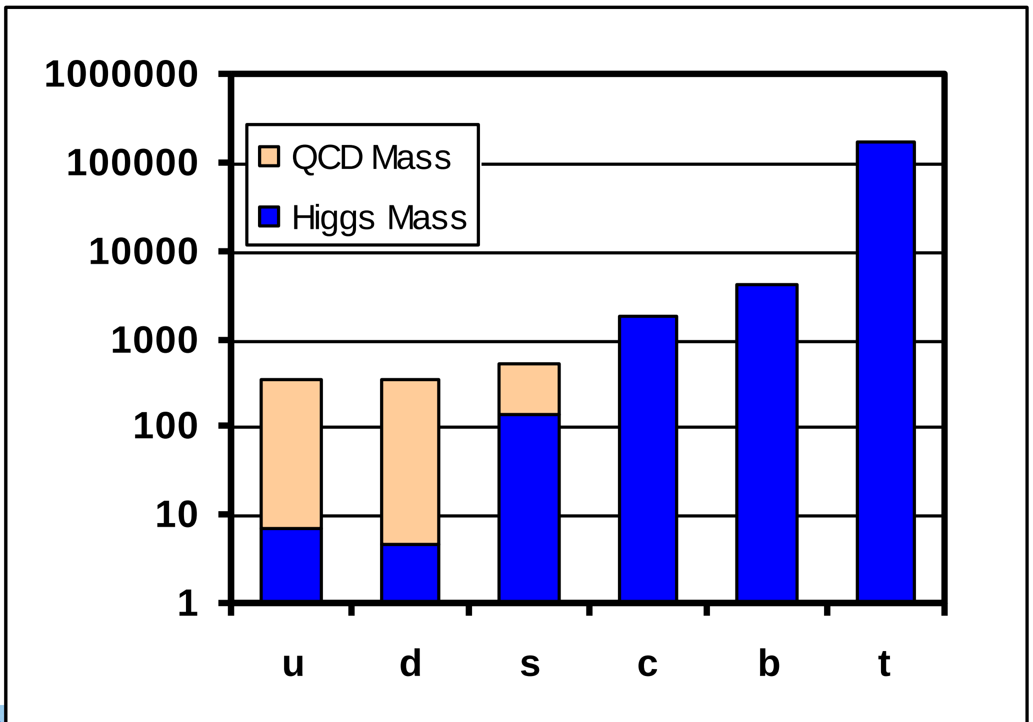
- the QCD Lagrangian:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\alpha}_{\mu\nu}F^{\mu\nu}_{\alpha}}_{\text{free gluon field}} - \underbrace{\sum_n \bar{\psi}_n \gamma^{\mu}[\partial_{\mu} - igA^{\alpha}_{\mu}t_{\alpha}]\psi_n}_{\text{interaction of quarks with gluon}} - \underbrace{\sum_n m_n \bar{\psi}_n \psi_n}_{\text{free quarks of mass } m_n}$$

- explicit chiral symmetry breaking
  - mass term $m_n\psi_n\psi_n$ in the QCD Lagrangian
- chiral limit: $m_u = m_d = m_s = 0$
  - chirality would be conserved
  - → all states have a 'chiral partner' (opposite parity and equal mass)
- real life
  - a_1 ($J^P=1^+$) is chiral partner of ρ ($J^P=1^-$): $\Delta_m \approx 500$ MeV
  - even worse for the nucleon: N^* ($\frac{1}{2}^-$) and N ($\frac{1}{2}^+$): $\Delta_m \approx 600$ MeV
  - → (small) current quark masses don't explain this
- chiral symmetry is also spontaneously broken
  - spontaneously = dynamically

Origin of mass

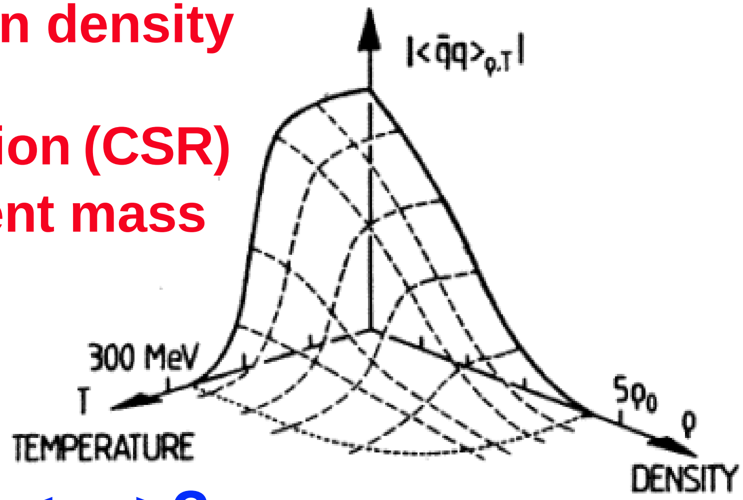
- **current quark mass**
  - **generated by spontaneous symmetry breaking (Higgs mass)**
  - **contributes ~5% to the visible (our) mass**



- **constituent quark mass**
  - **~95% generated by spontaneous chiral symmetry breaking (QCD mass)**

Chiral symmetry restoration

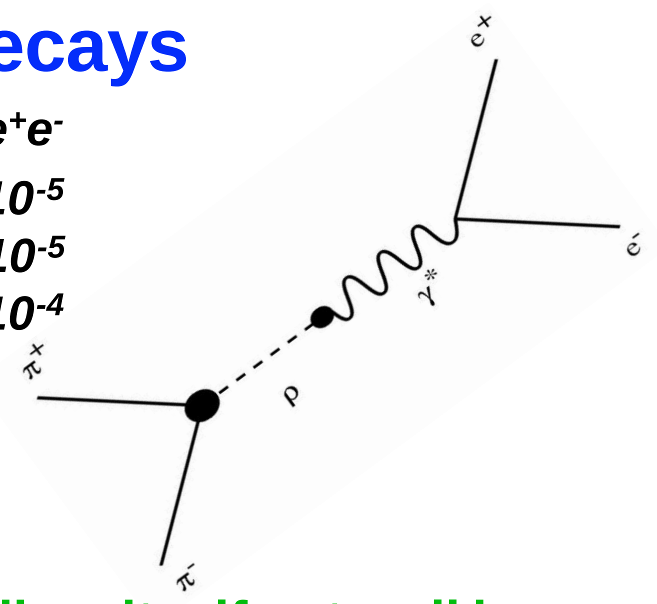
- spontaneous symmetry breaking gives rise to a nonzero 'order parameter'
  - QCD: quark condensate $\langle\bar{q}q\rangle \approx -250$ MeV^3
  - many models (!): hadron mass and quark condensate are linked
- numerical QCD calculations
  - at high temperature and/or high baryon density → deconfinement and <qq>→0
  - approximate chiral symmetry restoration (CSR)
  - → constituent mass approaches current mass
- Chiral Symmetry Restoration
  - expect modification of hadron spectral properties (mass m, width Γ)
- explicit relation between (m,Γ) and <qq>?
- QCD Lagrangian → parity doublets are degenerate in mass



CSR and low mass dileptons

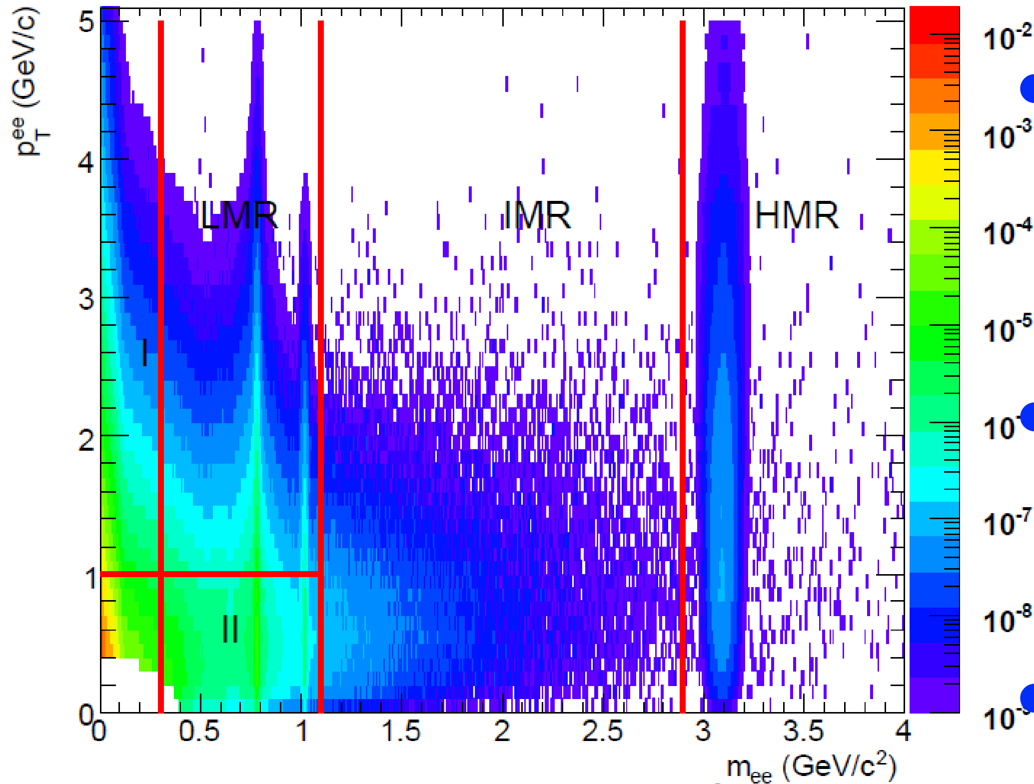
- what are the best probes for CSR?
- requirement: carry hadron spectral properties from (T, ρ_B) to detectors
  - relate to hadrons in medium
  - leave medium without final state interaction
- dileptons from vector meson decays

	m [MeV]	Γ_{tot} [MeV]	τ [fm/c]	BR→e^+e^-
ρ	770	150	1.3	4.7×10^{-5}
ω	782	8.6	23	7.2×10^{-5}
ϕ	1020	4.4	44	3.0×10^{-4}



  - best candidate: ρ meson
    - short lived
    - decay (and regeneration) in medium
    - properties of in-medium ρ and of medium itself not well known
  - ϕ meson ($m_\phi \approx 2 x m_K$) → ee/KK branching ratio!

Dilepton Signal



- **Low Mass Region:**
  $m_{ee} < 1.2$ GeV/c^2
  - **Dalitz decays of pseudo-scalar mesons**
  - **Direct decays of vector mesons**
  - **In-medium decay of ρ mesons in the hadronic gas phase**
- **Intermediate Mass Region:**
  $1.2 < m_{ee} < 2.9$ GeV/c^2
  - **correlated semi-leptonic decays of charm quark pairs**
  - **Dileptons from the QGP**
- **High Mass Region:**
  $m_{ee} > 2.9$ GeV/c^2
  - **Dileptons from hard processes**
    - **Drell-Yan process**
    - **correlated semi-leptonic decays of heavy quark pairs**
    - **Charmonia**
    - **Upsilons**
  - **→HMR probe the initial stage**
  - **Little contribution from thermal radiation**

- LMR: $m_{ee} < 1.2$ GeV/c^2
  - **LMR I** ($p_T \gg$ **m_{ee}**)
    quasi-real virtual photon region. Low mass pairs produced by higher order QED correction to the real photon emission
  - **LMR II (p_T<1GeV)**
    ***Enhancement* of dilepton discovered at SPS (CERES, NA60)**

Dilepton Signal II

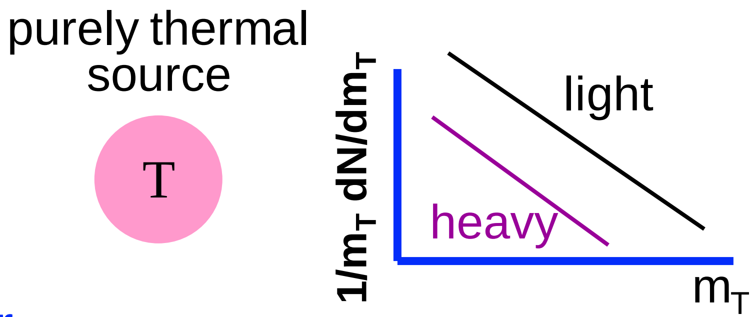
- Dileptons characterized by 2 variables: M, p_T
- M: spectral functions and phase space factors
- p_T: p_T - dependence of **spectral function** (dispersion relation)
  T - dependence of **thermal distribution** of "mother" hadron/parton
  M - dependent **radial flow** (β_T) of "mother" hadron/parton

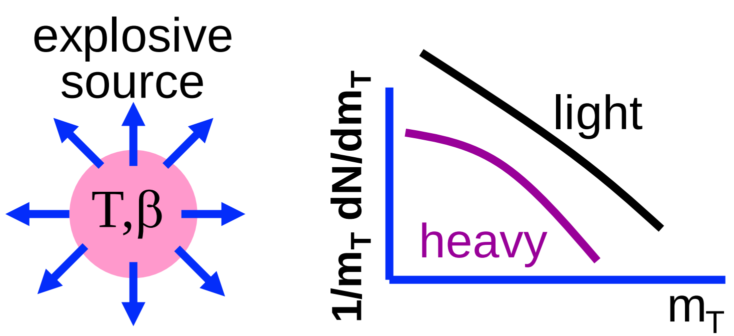
Note I: M Lorentz-invariant, not changed by flow

Note II: final-state lepton pairs themselves only weakly coupled

- dilepton p_T spectra superposition of 'hadron-like' spectra at fixed T
  - early emission: high T, low β_T
  - late emission: low T, high β_T
- final spectra from space-time folding over T- β_T history from $T_i \rightarrow T_{fo}$

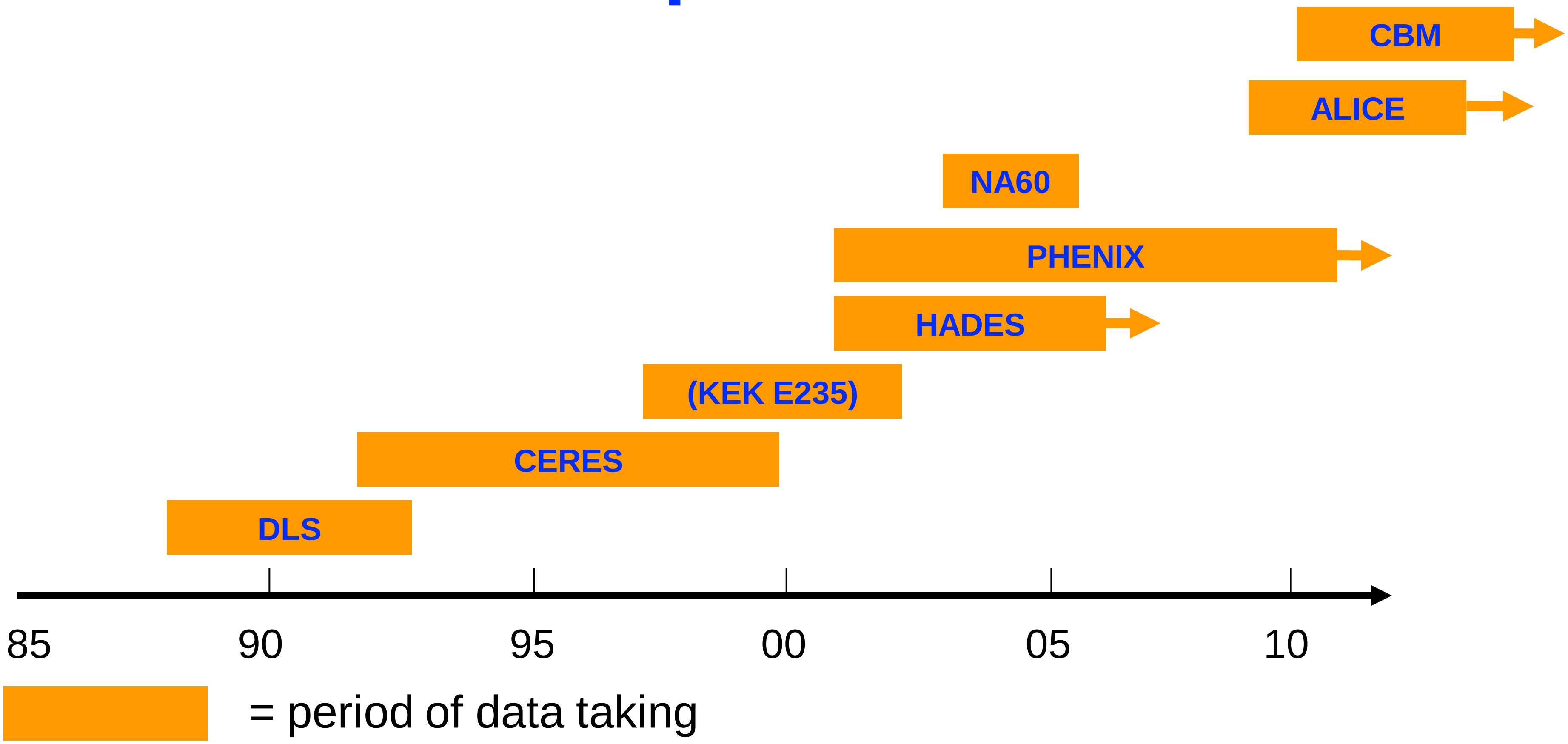
→ handle on emission region, i.e. nature of emitting source





HI low-mass dileptons at a glance

- time scale of experiments



HI low-mass dileptons at a glance

- energy scale of experiments